

THE NITROGEN ABUNDANCE OF ν INDI

R. A. Bell

(Received 1970 April 29)

AIAA Rejected

SUMMARY

A number of synthetic stellar spectra have been computed in order to derive the nitrogen abundance of the subgiant ν Indi. These spectra cover the (0, 0) sequence of the violet CN band and have been computed for various nitrogen abundances. By comparing the computed spectra with the observations it is found that nitrogen is underabundant by a factor of about 1000 relative to the Sun. This confirms the result of Harmer and Pagel that the deficiency of nitrogen is greater than the deficiency of carbon and other metals in this star.

1. INTRODUCTION

Przybylski (1962) pointed out that the violet CN bands were very weak in the spectrum of the high velocity subgiant ν Indi. He also showed that the spectral features and *UBV* colours of the star could not be explained by a binary hypothesis. Harmer & Pagel (1970) (hereafter referred to as HP) have used the CN bands to show that ν Indi is abnormally deficient in nitrogen. They found that, whilst carbon and other metals are deficient by a factor of about 15 relative to the Sun, nitrogen is deficient by a factor of between 60 and 120.

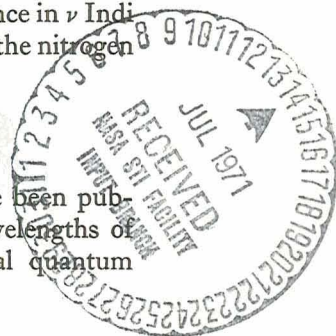
In their analysis, HP used both equivalent widths of individual rotational lines of the (0, 0) CN violet band and the depths of the (1, 1) and (3, 3) band heads. Owing to the great weakness of the CN rotational lines, it is hard to measure the equivalent widths accurately—the values of $\log (W/\lambda)$ given by HP are -5.40 or smaller. Furthermore, as HP pointed out, their analysis of the depths of the band heads required an assumption relating the fractional depression of the continuum to the curve of growth shift, X , which is proportional to the CN line absorption coefficient. The depths of the band heads are also affected by the instrumental profile of the spectrograph used to observe the star.

The analysis of molecular bands in stellar spectra is facilitated by the computation of synthetic stellar spectra, computed for various values of the relevant stellar atmosphere parameters. Comparison of observation and calculation allows the determination of the computed spectrum which best fits the observations and consequently gives the best value of the relevant parameters. This type of calculation is ideally suited to the problem of determining the nitrogen abundance in ν Indi since the violet CN bands can be readily calculated for various values of the nitrogen abundance.

2. CALCULATIONS

Wavelengths for many rotational lines of the CN violet band have been published by Weinard (1955), who has also given formulae enabling wavelengths of other lines to be computed. The branch, rotational and vibrational quantum

N71-74045



Code - none
NASA - CR - 119050
Pages - 7

number, J and v , and wavelength of each of the CN lines have been written on magnetic tape, the wavelengths being computed from Weinard's formulae or slight modifications thereof. The doublet splitting was allowed for by adding a term $\pm 0.0008J$ to the wavelengths given by the formulae. The magnetic tape also contains data on other molecular and atomic lines, taken from numerous sources, details being given in Bell (1970).

Two model atmospheres were computed using the temperature-optical depth relation given by Krishna Swamy (1967) viz

$$T^4(\tau) = \frac{3}{4}T_{\text{eff}}^4(\tau + 1.39 - 0.549 \exp(-0.76\tau) - 0.3 \exp(-12\tau))$$

which is intended to represent the solar temperature-optical depth relation. T_{eff} is the effective temperature. The opacity sources allowed for were H, H⁻, He⁻, Mg I and Si I (Travis & Matsushima 1968), electron scattering and Rayleigh scattering by H and H₂.

The six-colour photometry of Kron, Feinstein & Gordon (1966, unpublished) and measurements of neutral and ionized lines indicate that the effective temperature of ν Indi is lower than that of the Sun by between 0.10 and 0.15 in θ_{eff} , where $\theta_{\text{eff}} = 5040/T_{\text{eff}}$. The curve of growth analysis of the star, to be discussed in detail in a later paper, yields $[\text{Fe}/\text{H}] = -1.0$ for $\Delta\theta_{\text{eff}} = 0.10$ and $[\text{Fe}/\text{H}] = -1.2$ for $\Delta\theta_{\text{eff}} = 0.15$. The spectroscopic values of the surface gravity are $g = 1000 \text{ cm s}^{-2}$ and 250 cm s^{-2} for $\Delta\theta_{\text{eff}} = 0.10$ and 0.15 , respectively. The Parallax Catalogue value of $0''.030$ gives $M_v = +2.7$ and with $\Delta\theta_{\text{eff}} = 0.15$ and assuming the mass of ν Indi to be one solar mass, we find $g = 2500 \text{ cm s}^{-2}$. However, the individual parallax determinations are discordant, being $0''.046$ (Yale) and $0''.011$ (Cape), and the spectroscopic gravity seems to be preferable to that derived from the parallax. The influence of surface gravity on the results is examined subsequently. The parameters used for the model calculations were, therefore, $\Delta\theta_{\text{eff}} = 0.10$ and $g = 1000$ for the hotter of the two models and $\Delta\theta_{\text{eff}} = 0.15$ and $g = 250$ for the cooler and it was assumed that all the metals showed the same underabundance as iron. The hydrogen to helium ratio was taken to be 16 by number.

The model atmospheres and the magnetic tape containing data on the CN and other molecular and atomic lines then served as input data for the program which computed synthetic spectra for ν Indi. A complete description of this program has been given elsewhere (Bell 1970). However, a few points are particularly relevant to the present problem.

HP have used the equivalent widths of CH lines to show that $[\text{C}/\text{H}] = [\text{Fe}/\text{H}]$ on the assumption that $[\text{O}/\text{H}] = [\text{Fe}/\text{H}]$. It is necessary to assume an oxygen abundance to derive a carbon abundance because of CO formation. The HP abundances have been used in the present paper. Cohen (1968) and Cohen & Strom (1968) have also found $[\text{C}/\text{H}] = [\text{Fe}/\text{H}]$ in metal deficient stars. However, the exact values of carbon and oxygen abundances, and the gravity used for the model, are not critical as far as the CN abundance determination is concerned as long as the observed and computed CH equivalent widths agree. The partial pressures of CH and CN are given by $p(\text{CH}) = p(\text{C}) \cdot p(\text{H})/K_{\text{CH}}$ and $p(\text{CN}) = p(\text{C}) \cdot p(\text{N})/K_{\text{CN}}$ and if the computed CH equivalent widths are correct then the partial pressure of free carbon, $p(\text{C})$, is then adequately known for the purpose of computing the partial pressure of CN. Since the partial pressures will vary with optical depth, as will the fraction of carbon locked up in CO, and the computation of CH lines requires knowledge of the relevant CH parameters some error in the CN calculations will

occur from uncertainty in the abundance of free carbon. However, this error is certainly less than a factor of two.

The solution of the molecular equilibria equations with

$$[C/H] = [O/H] = [Fe/H]$$

and an assumed nitrogen abundance gives the number of CN molecules per gram of stellar material, $N(CN)$, as a function of optical depth. The line absorption coefficient at the centre of a CN line is

$$l_0 = \text{const } N(CN) \cdot S_J \cdot f_{v'v''} \exp(-((G_0(v'') + B_{v'} J(J+1))hc/kT))$$

where S_J is the Hönl–London factor, $f_{v'v''}$ the Franck–Condon factor (Jarman & Fraser 1953) and the exponential term allows for distribution over the vibrational and rotational levels. The constant contains atomic constants and the electronic oscillator strength and its value was obtained by fitting observed and computed lines of the CN (0, 1) band in the solar spectrum. The line absorption coefficient at wavelength λ , $l_v(\lambda)$, is computed as a function of optical depth from the equation

$$l_v(\lambda) = \sum_i l_{0,i} H(a, u_i)$$

where $H(a, u_i)$ is the Voigt function with $u_i = (\lambda - \lambda_i)/\Delta\lambda_D$ and $l_{0,i}$ is the line absorption coefficient at the centre of the i th line, which has wavelength λ_i . HP (private communication) have determined a total Doppler-broadening velocity (DBV), v , of 1.8 km s^{-1} for iron. This velocity contains both thermal and turbulent terms. The thermal velocity of CN molecules will be higher than that of iron atoms, owing to their lower mass, and if the microturbulent velocity is the same the DBV of CN will be 2.1 km s^{-1} while that of CH will be 2.6 km s^{-1} . For convenience, the value of 1.8 km s^{-1} was used for both CN and atomic lines but 2.6 km s^{-1} was used for CH lines. Since the CN lines are weak, the equivalent width of an individual line will be independent of DBV. In the present case the overlapping of the CN line absorption coefficients does depend on DBV but the strength of the band, which is composed of many weak lines, will be independent of DBV. The damping constant, a , for ν Indi is computed from the collisional damping constant relation

$$\log \frac{a}{a_\odot} = \log \frac{p}{p_\odot} + 0.7 \log \frac{\theta}{\theta_\odot} - \log \frac{v}{v_\odot}$$

and the solar damping constant, the pressures and temperatures being evaluated at an optical depth of 0.1 in the respective model atmospheres. The solar damping constant is taken to be 0.018. The damping constant is important only when strong lines are being considered and does not affect the weak bands of CN in ν Indi.

The line absorption coefficient is integrated over optical depth to give the optical depth in the line and the emergent flux in the line, $F(\lambda)$, evaluated by four point gaussian quadrature. The source function is taken to be the Planck function. The fluxes are computed at wavelengths 0.02 Å apart. The continuum fluxes, F_c , are also computed and the residual intensity, $R(\lambda)$, given by $R(\lambda) = (F_c - F(\lambda))/F_c$, found as a function of wavelength.

The spectra of ν Indi used by HP and for the present paper were photographed at a dispersion of 6.7 Å mm^{-1} . At this dispersion, the influence of the instrumental profile of the spectrograph on the observed spectrum is quite considerable and must be allowed for in any comparison of observed and computed spectra.

Veth (1969) and Griffin (1969) have used lasers to determine instrumental profiles for high dispersion stellar spectrographs. Veth has shown that the profile of the Ondrejov coude spectrograph is the convolution of the intensity distribution of light on the photographic plate with the photographic spread function, $S(\lambda)$, λ being the distance from the line centre. The central part of the profile is dominated by $S(\lambda)$ and the observed profile departs from this only at intensities less than 10^{-3} of the central intensity. From Fig. 4 of Veth* we have

$$S(\lambda) = \exp(-|\lambda|/q) \quad (1)$$

for the central part of the profile and we define λ_1 , λ_2 such that $S(\lambda_1) = 0.01$ and $S(\lambda_2) = 0.001$. Thus, from equation (1)

$$\int_0^{\lambda_1} S(\lambda) d\lambda = 100 \int_{\lambda_1}^{\lambda_2} S(\lambda) d\lambda.$$

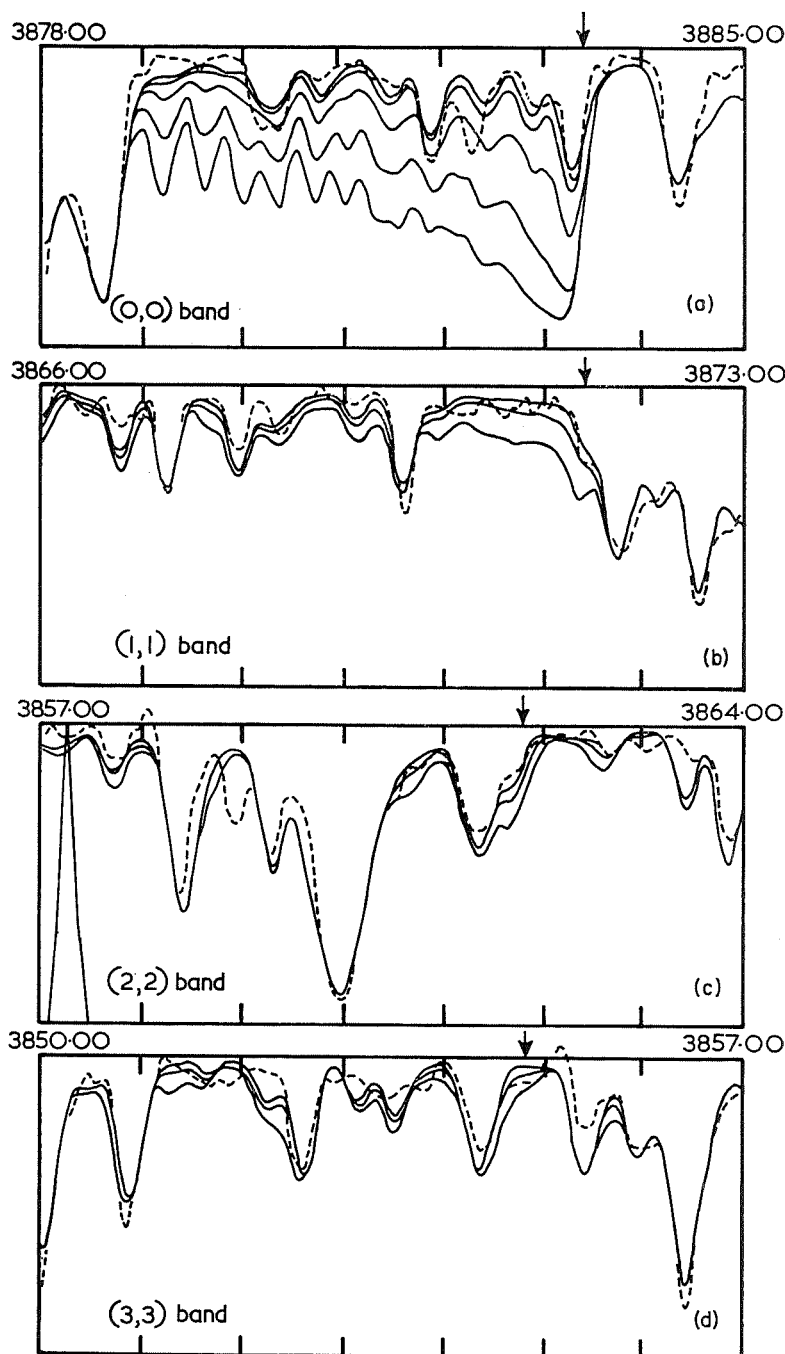
Consequently in the convolution of $S(\lambda)$ with the observed spectrum the effect of ignoring the part of the instrumental profile with $\lambda_2 > \lambda > \lambda_1$ can produce at most a difference of 1 per cent in the intensity of the observed spectrum at any wavelength. If we assume the above formula holds for the Radcliffe spectrograph then, from tracings of weak iron lines we find $\lambda_1 = 0.53 \text{ \AA}$ and $\lambda_2 = 0.79 \text{ \AA}$, the half-half width being 0.08 \AA .

The instrumental profile measured by Griffin departs from equation (1) at an intensity of about $10^{-2.5}$ of the central intensity and the wings contribute more to the profile. Following Veth and Griffin the errors caused by neglect of instrumental profile wings will amount to, at most, about 0.04 in computed residual intensity. This maximum error will occur only when the residual intensity in both wings of the instrumental profile differs by unity from that in the profile centre, a circumstance which does not occur when considering the CN bands. However, it would clearly have been desirable to have laser measurements of the Radcliffe profile rather than rely on measures of weak comparison lines, since uncertainties in the centre of the profile will also affect the computed spectrum.

The adopted instrumental profile is indicated, for comparison purposes, in Fig. 1(c). The computed residual intensities were convolved with this instrumental profile and then plotted using a Calcomp plotter. Examples of these plots are given in Fig. 1 (a)–(d), the CN lines being computed for various nitrogen abundances. The observed spectrum, represented by the dashed line, is also given in these figures.

Owing to the weakness of the CN lines, as may be seen from cursory inspection of Fig. 1, a number of atomic lines can be seen in the wavelength region shortward of the (0, 0) CN band head. The profiles of most of these are satisfactorily represented in the calculations but other lines require changes in their oscillator strengths or in element abundances to give good agreement between observation and calculation. The Fe I line at $\lambda 3883.28$ obscures the (0, 0) band head. The computed intensity of the $\lambda 3882.33$ (Ti I) line is too weak whilst the agreement between observation and calculation for the $\lambda 3881.87$ (Co I)– $\lambda 3881.92$ (Ni II) blend is quite satisfactory.

* It should be noted that Veth's formulation of $S(\lambda)$ for the central and wing profiles as given in the text of his paper should be interchanged, to make them compatible with Veth's Fig. 4 and with Griffin's wing formula.



FIGS 1(a), (b), (c) and (d) show the observed spectrum of ν Indi, represented by the dashed line, and a number of synthetic spectra, represented by the solid lines. The synthetic spectra have been computed for different nitrogen abundances. For Fig. 1(a) the strongest CN band has been computed with $[N/H] = -1.0$. The other abundances used in Fig. 1(a) are $[N/H] = -1.5, -2.0, -2.5$ and -3.0 . The spectra shown in Figs 1(b), (c) and (d) have been computed for $[N/H] = -2.0, -2.5$ and -3.0 , the CN lines sometimes being so weak that the latter two are indistinguishable. The arrows represent the wavelengths of the band heads.

The instrumental profile is shown, in emission, in Fig. 1(c).

3. RESULTS

Spectra computed for the hotter model, $\Delta\theta_{\text{eff}} = 0.10$, are shown in Fig. 1 (a)–(d) for the wavelength regions around the (0, 0), (1, 1), (2, 2) and (3, 3) band heads. There is, however, overlapping of the different bands, and lines of the (1, 1) band can be seen in the diagram showing the (2, 2) band head. The theoretical spectra shown in Fig. 1(a) have been computed using nitrogen abundances, $[N/H]$, of -1.0 , -1.5 , -2.0 , -2.5 and -3.0 whilst the theoretical spectra of Figs 1(b), (c) and (d) have been computed for $[N/H] = -2.0$, -2.5 and -3.0 . By comparing the computed spectra with the observed one, it is seen that the nitrogen abundance is certainly less than $[N/H] = -2.0$ and in fact may be lower by a further factor of ten. Unfortunately the CN lines are so weak that the residual intensities in the observed spectrum are strongly affected by the location of the continuum. If greatest weight is given to the wavelength region just shortward of the (0, 0) band head, where the CN lines are strongest, $[N/H] = -3.0$ appears to be the best value of the nitrogen abundance. The spectra computed using the cooler model, $\Delta\theta_{\text{eff}} = 0.15$, are very similar to those computed using the hotter model and give a similar nitrogen abundance.

As well as the continuum location, the nitrogen abundance derived above is subject to uncertainties caused by uncertainty in the electronic oscillator strength and in the carbon and oxygen abundances and the gravity of the star. The damping constant and Doppler-broadening velocity do not affect the results. The electronic oscillator strength, derived by fitting observed and computed equivalent widths of CN lines of the (0, 1) band in the solar spectrum, is probably correct to within a factor of two. Increasing the gravity of the model, for fixed carbon, nitrogen, oxygen and hydrogen abundances, will decrease the strength of the CN lines since the increase in pressure (Warner 1964) will increase the fraction of carbon locked up in CO. Similarly decreasing the carbon abundance or increasing the oxygen abundance will weaken the CN lines. However, the only way in which the CN lines can be weakened without simultaneously weakening the CH lines is by decreasing the nitrogen abundance. The uncertainty in nitrogen abundance, due to uncertainty in carbon and oxygen abundances and in the gravity, is estimated as a factor of two since the equivalent widths of the CH lines, computed from the models of Section 2, are in good agreement with observation. In view of the uncertainty in gravity and in the instrumental profile and continuum location, the best estimate of nitrogen abundance is $[N/H] = -3.0$, although it may be as high as -2.5 or as low as -3.3 .

It is not certain that the accuracy of the nitrogen abundance determination will be greatly improved by observing the violet CN bands in ν Indi at higher dispersion. The reason for this is the uncertainty in continuum location. It is clearly of importance, for nucleosynthesis reasons, to obtain a nitrogen abundance which is as accurate as possible and consequently it would be of great interest to observe the ultra-violet NH bands in ν Indi and other metal deficient stars. The rotational lines of these bands are very strong in the solar spectrum (Moore, Minnaert & Houtgast 1966). They should consequently be visible in the spectrum of ν Indi, since their intensity is dependent on NH abundance, which is affected by the nitrogen underabundance, whilst the CN bands depend on the CN abundance which is affected by the underabundances of both carbon and nitrogen. The analysis of ν Indi would be materially assisted by simultaneous analysis of a star such as HD 25329, which is metal deficient but which has sufficiently strong CN bands for them to be used to

determine a nitrogen abundance. It would also be of great interest to observe the ultra-violet OH bands since they could be used to yield an oxygen abundance. Owing to the complexity of the $\lambda 3300$ wavelength region it will be necessary to use synthetic spectra to analyse the OH and NH bands.

4. CONCLUSIONS

A comparison of observed and computed spectra for the (o, o) sequence of the CN violet bands gives a nitrogen abundance of $[N/H] = -3.0$ for ν Indi. However, the uncertainties in gravity, continuum location, instrumental profile and electronic oscillator strength may cause the abundance to be as high as $[N/H] = -2.5$ or as low as $[N/H] = -3.3$. Observation of the ultra-violet NH bands may give a more accurate nitrogen abundance.

ACKNOWLEDGMENTS

I would like to thank Mrs D. L. Harmer and Dr B. E. J. Pagel for suggesting this problem and for allowing me to use their tracings of ν Indi. I am most grateful to Mr John Ohlmacher, who ran the necessary programs on the University of Maryland Univac 1108 computer. Part of the computer time for this project was supplied by the University of Maryland Computer Science Center under Grant NsG 398. I also wish to acknowledge the support of the U.S. National Science Foundation under Grant GP 8698 and to thank the Science Research Council for a Fellowship.

Royal Greenwich Observatory, Herstmonceux Castle, Sussex.

(On sabbatical leave from Astronomy Program, University of Maryland)

REFERENCES

- Bell, R. A., 1970. *Mon. Not. R. astr. Soc.*, **148**, 25.
Cohen, J. G., 1968. *Astrophys. Lett.*, **2**, 163.
Cohen, J. G. & Strom, S. E., 1968. *Astrophys. J.*, **151**, 623.
Griffin, R. F., 1969. *Mon. Not. R. astr. Soc.*, **143**, 319.
Harmer, D. L. & Pagel, B. E. J., 1970. *Nature*, **225**, 349.
Jarmain, W. R. & Fraser, P. A., 1953. *Proc. Phys. Soc. London*, **66A**, 1153.
Krishna Swamy, K. S., 1967. *Astrophys. J.*, **150**, 1161.
Moore, C. E., Minnaert, M. H. & Houtgast, J., 1966. *Nat. Bur. Stand., Monograph No. 61*.
Przybylski, A., 1962. *Publ. astr. Soc. Pacific*, **74**, 230.
Travis, L. & Matsushima, S., 1968. *Astrophys. J.*, **154**, 689.
Veth, C., 1969. *Bull. astr. Inst. Netherl.*, **20**, 312.
Warner, B., 1964. *Observatory*, **84**, 258.
Weinard, J., 1955. *Ann. Astrophys.*, **18**, 334.

RECEIVED
A.I.A.A.
71 JUN 23 PM 2:38
T.I.S. LIBRARY